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Full Length Research Paper

Effect of plant density on the characteristics of photosynthetic apparatus of garlic (*Allium sativum var. vulgare* L.)

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Field experiments were conducted to study green garlic response to the following plant densities: 300,000; 450,000; 600,000; 750,000 and 900,000 plants/ha. The experiment lasted for two years. Plant measurements started 40 days after planting (DAP) and were performed at ten-day intervals. Eight measurements per year were made in total and the following traits were measured: leaf number per plant, leaf surface area and leaf area index (LAI). These parameters were used to determine the effects of stand density on the photosynthetic apparatus of the garlic plant. These effects were found to be present, but to varying degrees. Stand density had the strongest effect on LAI and the smallest on leaf area. The data collected during the experiment and the appearance of the garlic plants themselves showed that the crop performed best at moderate stand densities (600,000 and 750,000 plants/ha). At such densities, garlic developed a powerful photosynthetic apparatus and the bulbs were large and uniform.

Key words: Garlic, plant density, leaf number per plant, leaf area, LAI.

INTRODUCTION

The photosynthetic apparatus performs photosynthesis, which involves the production of organic matter (carbohydrates, protein and fats). The leaves are the most important part of the plant for photosynthetic activity. Photosynthesis depends on a large number of factors. Foremost among these is the chlorophyll content of the leaves, followed by the leaf surface area, which determines how much sunlight will be absorbed by the plant. Photosynthesis also depends greatly on the leaves' position on the plant, the activity of photosynthetic and respiratory enzymes, concentrations of atmospheric CO_2 and O_2, and so on. In addition, photosynthesis depends on the genotype (Sarić, 1979).Different parameters are used to assess the characteristics of the photosynthetic apparatus. The most important of them are leaf number per plant, leaf area per plant, and leaf area index (LAI), which represents a crop's total leaf area per unit area (m^2/ha). Garlic develops 8 to 14 leaves. The photosynthetic apparatus of a cultivated plant can be acted upon via plant density (leaf number per unit area). Plant density depends on the genotype, environmental factors, cultural practices, etc. It should be noted that a thinner stand promotes the expression of an individual plant's potential, whereas denser stands are conducive to a greater expression of the plants' collective potential (crop potential). This has been noted by many authors, especially those working in the field of plant physiology (Rubin, 1979; Jakubova, 1988; Kastori, 1989).

Many researchers have studied the effects of stand density on garlic. Data are also available for leaf number per plant, leaf area, and leaf area index. Studies have shown that there is no single, universal plant density that would be optimal for a garlic crop regardless of the soil and climatic conditions it is grown under. Llosas and Fernandez, (1984) argue that the ideal stand density for

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Abbreviations: DAP, Days after planting; **LAI,** leaf area index.

Table 1. Mean monthly temperature and monthly rainfall during the growing season for the two years of experimentation (2007–2008).

Month	Temperature (°C)		Rainfall (mm)	
	2007	2008	2007	2008
March	9.3	9.1	93.3	75.5
April	12.8	13.5	1.0	27.3
May	18.3	18.3	96.1	14.8
June	22.2	22.3	114.7	62.5
July	23.5	22.4	17.2	56.8
Mean (sum)	17.2 (86.1)	17.1 (85.6)	64.5 (322.3)	47.4 (236.9)

garlic is about 800,000 plants/ha. They note that this particular density is very high, but that it only negatively affects bulb uniformity. According to Lewis et al. (1995), garlic responds best to a plant population of 330,000 individuals/ha, as this density allows the plant in general and the leaves in particular to develop optimally. Results obtained by Muro et al. (2000) indicate that garlic leaf parameters (leaf number per plant, leaf area and leaf mass) reach their maximum values three weeks before the bulbs are harvested. Ahmad and Iqbal (2002) studied plant densities of up to 2,000,000 plants/ha, but they achieved the best results with stands of moderate density (around 600,000 plants/ha).

Information can also be found that suggests a positive correlation between crop growth rate (CGR) and the leaf area index, especially in the mid-growing season (Haque et al., 2002b). There is evidence that garlic grows best when there are about 600,000 plants/ha (Moravčević et al., 2011). According to Karaye and Yakubu (2006), garlic plants become more luxuriant in thinner stands, while bulb yield increases at greater plant populations. The authors suggest that garlic should be grown in a thick stand to give priority to yield. Having studied plant populations between 330,000 and 1,300,000 plants per hectare, Kilgori et al. (2007a, b) found that garlic responded best to a stand of 600,000 plants/ha.

The objective of this study was to determine the response of garlic leaves (photosynthetic apparatus) to stand density in order to identify plant populations that will promote the development of a powerful and highly functional leaf system with a great photosynthetic capacity. The garlic plants were studied on a fertile soil in a continental climate.

MATERIALS AND METHODS

A two-year field experiment with four replications was carried out during 2007 and 2008 at experimental estate "Radmilovac" of the Faculty of Agriculture of Belgrade University (Radmilovac – Republic of Serbia; Long 44.45°N; Lat 20.35°E; 130 m a.s.l). The experimental unit size was 4 m^2 (2 × 2 m) and the treatments (different plant densities) were set up as a randomized block design. Primary tillage was performed in autumn (November) down to 30 cm soil depth. Just before planting in mid-March, the seedbed was prepared and the first batch of mineral fertilizer was applied (15:15:15 NPK, 400 kg/ha).Garlic was planted on the 23rd and 24th of March using outer ring cloves with an average individual weight of 1.74 g in 2007 and 1.94 g in 2008. Interrow spacing was consistent throughout the crop (25 cm), while the distance between the plants within the row ranged from 4.4 to 13.3 cm. This produced stand densities of 300,000 (G1), 450,000 (G2), 600,000 (G3), 750,000 (G4) and 900,000 (G5) plants/ha. The experimental material was the green garlic cultivar Piros, developed at the National Institute for Vegetable Crops at Smederevska Palanka (Republic of Serbia). Standard cultural practices, such as top dressing, hoeing and protection against pests and diseases, were used. All of them were performed manually.Measuring began 40 days after planting (DAP), when the plants developed around four leaves each. The measurements were taken at ten-day intervals using 20 samples (from each experimental unit), with 10 plants per sample. Eight rounds of measurements were made overall and the measured characteristics were leaf number per plant, leaf area and leaf area index (LAI). Leaf number per plant was determined by counting all the leaves that had developed to at least half their eventual size. In effect, we counted up all the leaves that were capable of conducting a significant amount of photosynthetic activity. Furthermore, the area of the leaf (lamina) was determined according to the leaf parameter method by Džamić et al. (2001) and expressed as cm^2. The method calculates the area as a product of leaf length, leaf width and a correction factor, which we determined ourselves (0.72). While LAI was determined using the standard procedure (Hunt, 1978; Kastori, 1989) and expressed as m^2 leaf area per unit land area (m^2).

The two years of study differed significantly in climatic terms (Table 1). The year 2007 was much more favourable, especially with respect to precipitation. The soil used in the study was of the eutric cambisol that had the following chemical properties: pH 5.60 (in KCl), 2.51% humus content, 0.11% total nitrogen, 11.9 mg phosphorus, and 21.2 mg potassium per 100 g/soil. The soil was therefore, moderately acidic and had a medium supply of humus and phosphorus and a good supply of potassium.

Statistical analysis

Statistical analysis (ANOVA) was performed using the SPSS version 16.0 and the differences between the means were compared using the criterion of LSD-test at p = 0.05 and 0.01. The one-year results are shown in tables, while the two-year means are presented in figures.

RESULTS

Leaf number per plant

At the time of Measurement I (40 DAP), the plants had 4.22 leaves on average (Figure 1). The number of leaves per plant kept rising steadily over a prolonged period and then stopped increasing about 30 days after Measurement IV (70 DAP) on an average for the two years. The average number of leaves at that time was 7.02. This was the expression of the characteristic in 2007 as well (Table 2), but the maximum value of the parameter was higher (8.2). In 2008, the maximum number of leaves (6.07) was recorded at Measurement VIII (the last one). Another maximum was recorded in this case - 5.99 at Measurement VI (90 DAP). Significant differences among the different plant populationtreatments were observed at different times. The first differences were noted at Measurement I in both years. They were more pronounced in 2008 (Table 3). The same differences were found at Measurements IV and V in 2007 and at the time of the last measurement in 2008. The largest differences were mostly found between the plants from the thinnest stands (300,000 and 450,000 plants/ha) and those from the densest (900,000 plant/ha).

Leaf area per plant

At the start of the measurements (40 DAP), the average leaf area was 41.55 cm^2 (Figure 2). Between Measurement I and VI (90 DAP), leaf area was on a steady increase, reaching 156.47 cm^2. From that time on, the area began to decrease sharply and reached 97.98 cm^2 when the last measurement was made (110 DAP).

The expression of leaf area was pronounced in 2007, with average values ranging from 51.53 to 189.17 cm^2 (Table 4). The smallest leaf area value was recorded at Measurement I (40 DAP) and the largest at Measurement VI (90 DAP). The leaf area dynamics were the same in 2008 (Table 5), but the values were lower, ranging from 31.57 (40 DAP) to 123.77 cm^2 (90 DAP). Between Measurements VI and VIII, leaf area per plant decreased rapidly, especially in 2007. Plant density affected this trait only at Measurements IV and V (70 to 80 DAP), when smaller plant populations had a larger leaf area. The effect of stand density was therefore greater in 2007.

Leaf area index (LAI)

LAI was initially 0.24 m^2/m^2 (Figure 3) and increased rapidly until Measurement IV (70 DAP) after which it reduced and the characteristic amounted to 0.93 m^2/m^2 at Measurement VI (90 DAP). In the last measurement (110 DAP), the two-year mean LAI value was 0.58 m^2/m^2. In both years of the experiment, LAI increased until Measurement VI (90 DAP), when it reached 1.12 m^2/m^2 and 0.75 m^2/m^2, respectively (Tables 6 and 7). The decrease of LAI after Measurement VI (90 DAP) was more pronounced in 2007. Plant density had a significant effect on LAI in both years, and the extent of this influence varied in the course of the experiment. Of note was the treatment with the smallest plant population (300,000 plants/ha), whose LAI at Measurement I (40 DAP) was already significantly lower than those of the other plant densities, which did not differ significantly among each other. This relation between the thinnest stand and the rest of the treatments was maintained until the last measurement (110 DAP). The treatment with 450,000 plants/ha showed similar behaviour relative to the larger plant populations (750,000 and 900,000 plants/ha). Differences between the two densest stands became significant only at measurements VI through VIII (90 to 110 DAP).

DISCUSSION

Leaf number per plant is an important factor for obtaining good results in crop production. Other factors, however, play important roles as well (genotype, overall level of plant development and climate). This has been pointed out by many researchers studying cultivated plants. Leaf number per plant, as a rule, increases up to a certain point in plant development and then begins to decrease (Llosas and Fernandez, 1984, Dalen, 1992; Lewis et al., 1995). Our present findings partially reflect these tendencies. A difference was observed in 2008, when a severe drought changed the leaf formation pattern and the leaves kept forming until the last measurement. Garlic has a characteristic response to such crop moisture conditions. The plant also responds to stand density and there are data available indicating that denser stands result in fewer leaves (Muro et al., 2000; Karaye and Yakubu, 2006; Rahman et al., 2004). Our present results support this observation.Leaf area is the key parameter in the manifestation of photosynthesis, as it determines how much sunlight will be absorbed by the crop. This is why this parameter is given special attention in physiological studies (Jelenić and Džamić, 1989; Lawlor, 1995). The longevity of the foliar system (the duration of the period during which it is capable of photosynthesis) is alsoimportant as discussed by Rubin (1979). Leaf area depends on a range of factors, but most notably on the amount of precipitation and fertiliser use. It should be the largest at the time during which conditions for photosynthesis are optimal, and in garlic, according to Kawecki and Krynska (1968), this period occurs in the month of June. This was the case in the present study. It is difficult to precisely define the term “optimal leaf area”, because crops are grown under different environmental conditions. Some researchers argue that the optimum

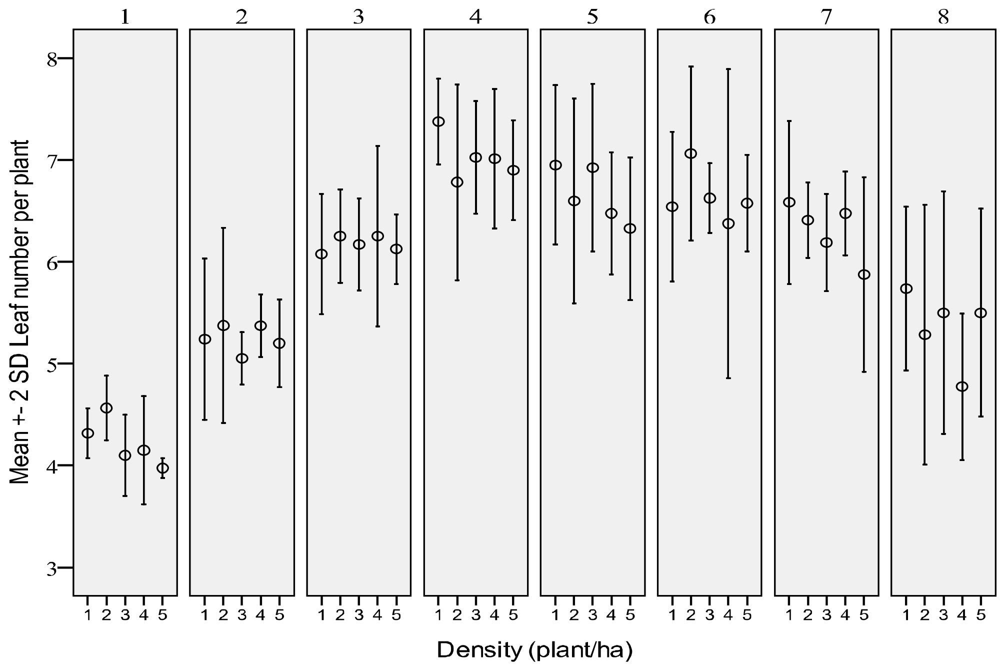

Figure 1. Leaf number per plant (two-year means) measurement.

Table 2. Leaf number per plant in 2007.

Density (plants/ha)	Leaf number per plant							
	I	II	III	IV	V	VI	VII	VIII
300,000 (G1)	4.25	5.58	6.67	8.92	8.00	7.25	7.17	4.73
450,000 (G2)	4.50	5.69	7.31	7.75	7.69	7.69	7.19	4.94
600,000 (G3)	4.00	5.50	6.80	8.40	8.05	7.45	6.43	4.55
750,000 (G4)	4.25	5.65	7.00	8.03	7.20	6.95	6.70	4.00
900,000 (G5)	4.00	5.55	7.25	7.90	7.35	7.05	6.50	5.05
Average	4.20	5.59	7.01	8.20	7.66	7.28	6.80	4.65
LSD 0.05	0.42	0.57	0.64	0.59	0.61	1.11	0.88	1.16
0.01	0.58	0.81	0.90	0.83	0.86	1.55	1.23	1.62

Measurements I = 40 DAP, II = 50 DAP, III = 60 DAP, IV = 70 DAP, V = 80 DAP, VI = 90 DAP, VII = 100 DAP, and VIII = 110 DAP.

Table 3. Leaf number per plant in 2008.

Density [plants/ha]	Leaf number per plant							
	I	II	III	IV	V	VI	VII	VIII
300,000 (G1)	4.38	4.91	5.48	5.83	5.90	5.83	6.00	6.75
450,000 (G2)	4.63	5.06	5.19	5.81	5.50	6.44	5.63	5.63
600,000 (G3)	4.20	4.60	5.54	5.65	5.80	5.80	5.95	6.45
750,000 (G4)	4.05	5.09	5.50	6.00	5.75	5.80	6.25	5.55
900,000 (G5)	3.95	4.85	5.00	5.90	5.30	6.10	5.25	5.95
Average	4.24	4.90	5.34	5.84	5.65	5.99	5.81	6.07
LSD 0.05	0.41	0.56	0.63	0.79	0.62	0.71	0.81	0.80
0.01	0.58	0.79	0.88	1.11	0.88	0.99	1.14	1.13

Measurements I = 40 DAP, II = 50 DAP, III = 60 DAP, IV = 70 DAP, V = 80 DAP, VI = 90 DAP, VII = 100 DAP, and VIII = 110 DAP.

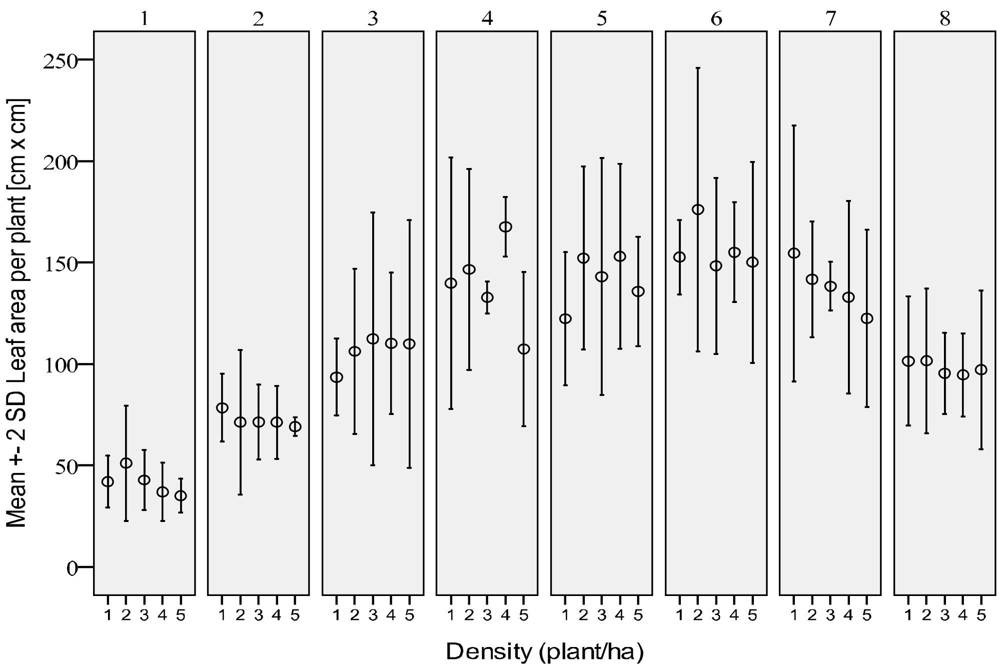

Figure 2. Leaf area per plant (two-year means) measurement.

Table 4. Leaf area per plant in 2007.

Density [plants/ha]	Leaf area per plant (cm^2)							
	I	II	III	IV	V	VI	VII	VIII
300,000 (G1)	51.68	95.00	113.42	180.68	143.05	189.58	186.34	93.16
450,000 (G2)	65.21	88.07	150.49	209.38	201.73	209.82	162.04	96.43
600,000 (G3)	49.92	91.18	125.77	167.94	178.15	187.46	156.92	96.41
750,000 (G4)	46.41	87.11	127.14	218.41	191.85	190.44	158.18	87.52
900,000 (G5)	44.42	88.70	144.91	132.74	149.27	168.55	132.63	84.47
Average	51.53	90.01	132.35	181.83	172.81	189.17	159.22	91.60
LSD 0.05	21.78	18.88	40.82	45.18	35.4	43.63	55.03	40.36
0.01	30.51	26.47	57.23	63.34	49.65	61.17	77.15	56.59

Measurements I = 40 DAP, II = 50 DAP, III = 60 DAP, IV = 70 DAP, V = 80 DAP, VI = 90 DAP, VII = 100 DAP, and VIII = 110 DAP.

leaf area is that area which allows garlic plants to maximize their photosynthetic activity and subsequently produce high yields as a result (Stahlschmidt et al., 1997). In our study, favourable conditions regarding precipitation led to a better expression of leaf area per plant in 2007. Plant density did not have a major effect on leaf area, which has to do with the morphology of that part of the plant. Garlic has narrow, erect leaves (small surface area) that do not overshadow each other very much, which is good for photosynthesis (William et al., 1997; Islam et al., 2004).

LAI is a very good indicator of a plant's photosynthetic capacity and is also very important in determining the levels of photosynthetic activity and yield. The goal is to attain such LAI dimension that will result in optimal photosynthetic activity. These dimensions are directly linked to leaf surface per plant and plant density. Under normal growing conditions, plant density is the more dominant factor. According to Ladesma et al. (1997) and Haque et al. (2002a), the highest LAI values in garlic are found around 80 days after the crop is established, which is the period of intensive bulb formation. Mirzaei et al. (2007) have shown that garlic LAI averages 0.85m^2/m^2, which is very low. Optimal values of this parameter are highly variable and depend on many factors. Foremost among these is plant density, with moderately dense stands being the most favourable. Such optimal density is achieved by having 600,000 to 900,000 plants/ha (Dawar

Table 5. Leaf area per plant in 2008.

Density [plants/ha]	Leaf area per plant [cm²]							
	I	II	III	IV	V	VI	VII	VIII
300,000 (G1)	32.21	61.78	73.46	98.87	101.53	115.75	122.66	109.66
450,000 (G2)	36.97	54.35	61.92	83.74	102.56	142.38	121.35	106.52
600,000 (G3)	35.69	51.55	98.93	97.49	107.86	109.32	119.72	94.32
750,000 (G4)	27.38	55.40	93.11	116.70	114.05	119.66	107.58	101.59
900,000 (G5)	25.58	49.41	74.89	81.95	122.19	131.75	112.23	109.74
Average	31.57	54.50	80.46	95.75	109.64	123.77	116.71	104.37
LSD 0.05	14.27	19.64	47.73	32.11	45.21	47.15	26.34	31.60
0.01	20.01	27.53	66.91	45.01	63.38	66.10	36.93	44.30

Measurements I = 40 DAP, II = 50 DAP, III = 60 DAP, IV = 70 DAP, V = 80 DAP, VI = 90 DAP, VII = 100 DAP, and VIII = 110 DAP.

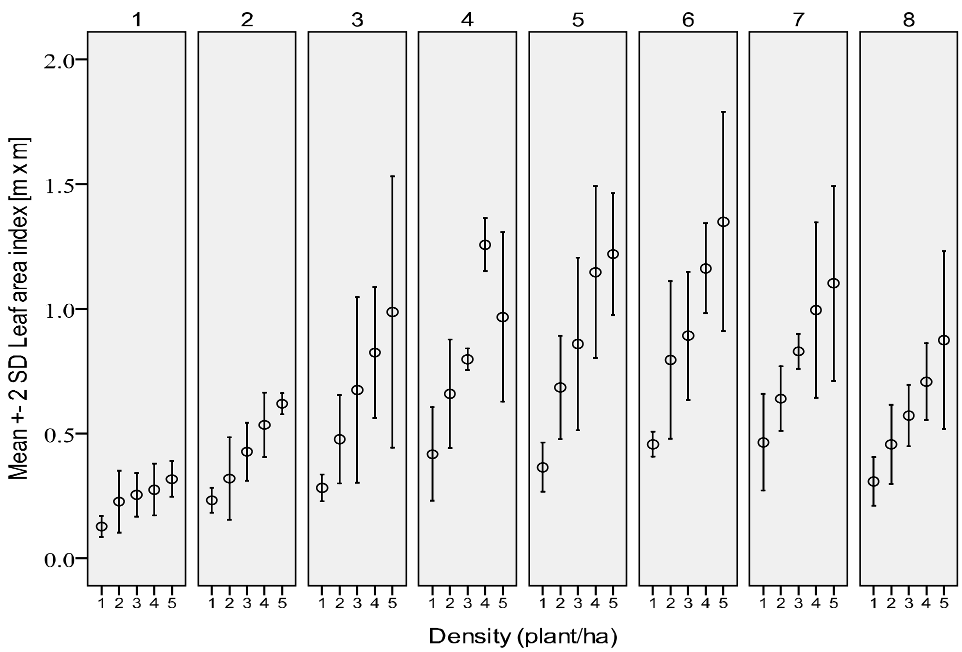

Figure 3. Leaf area index (two-year means) measurement

Table 6. Leaf area index (LAI) in 2007.

Density [plants/ha]	Leaf area index (m²)							
	I	II	III	IV	V	VI	VII	VIII
300,000 (G1)	0.16	0.29	0.34	0.54	0.43	0.57	0.56	0.28
450,000 (G2)	0.29	0.40	0.68	0.94	0.91	0.94	0.73	0.43
600,000 (G3)	0.30	0.55	0.75	1.01	1.07	1.12	0.94	0.58
750,000 (G4)	0.35	0.65	0.95	1.64	1.44	1.43	1.19	0.66
900,000 (G5)	0.40	0.80	1.30	1.19	1.34	1.52	1.19	0.76
Average	0.30	0.54	0.81	1.06	1.04	1.12	0.92	0.54
LSD 0.05	0.12	0.11	0.28	0.26	0.24	0.23	0.29	0.24
0.01	0.17	0.15	0.39	0.37	0.33	0.32	0.41	0.34

Measurements I = 40 DAP, II = 50 DAP, III = 60 DAP, IV = 70 DAP, V = 80 DAP, VI = 90 DAP, VII = 100 DAP, and VIII = 110 DAP.

Table 7. Leaf area index (LAI) in 2008.

Density [plants/ha]	Leaf area index (m^2)							
	I	II	III	IV	V	VI	VII	VIII
300,000 (G1)	0.10	0.19	0.22	0.30	0.30	0.35	0.37	0.33
450,000 (G2)	0.17	0.24	0.28	0.38	0.46	0.64	0.55	0.48
600,000 (G3)	0.21	0.31	0.59	0.58	0.65	0.66	0.72	0.57
750,000 (G4)	0.21	0.42	0.70	0.88	0.86	0.90	0.81	0.76
900,000 (G5)	0.23	0.44	0.67	0.74	1.10	1.19	1.01	0.99
Average	0.18	0.32	0.49	0.57	0.67	0.75	0.69	0.62
LSD 0.05	0.06	0.11	0.36	0.19	0.34	0.26	0.18	0.19
0.01	0.08	0.15	0.51	0.26	0.48	0.36	0.25	0.27

Measurements I = 40 DAP, II = 50 DAP, III = 60 DAP, IV = 70 DAP, V = 80 DAP, VI = 90 DAP, VII = 100 DAP, and VIII = 110 DAP.

et al., 2005; Moravčević et al., 2011). In the present study, LAI behaved as was expected, in accordance with the aforementioned literature. The highest expression of LAI coincided with the period of intensive insolation (June), especially in 2007 (optimal precipitation). It has been confirmed that in a crop such as garlic with its characteristic plant architecture LAI manifests itself to a greater extent in a denser stand, which is of particular importance for obtaining high yields of top quality.

Conclusion

Our study has fulfilled its goal of attempting to determine how garlic behaves in stands of different density with respect to photosynthesis. These findings show that plant density does affect the photosynthetic apparatus of this crop and that the optimal garlic plant populations for photosynthesis are 600,000 to 900,000 plants/ha.

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